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DEVELOPMENT OF LIGHT WEIGHT SOLID LUBRICATED BEARING RETAINERS.(U)
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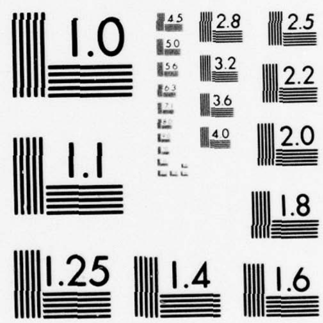
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DEVELOPMENT OF LIGHT WEIGHT SOLID LUBRICATED BEARING RETAINERS

Westinghouse Research & Development Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235

September 1978

TECHNICAL REPORT AFAPL-TR-78-72
Final Report for Period April 1977-May 1978

AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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A materials development program was undertaken in an effort to develop a high strength-to-weight ratio self-lubricating composite for use as a solid lubricating retainer in ball bearings operating at speeds up to 60,000 rpm. The program encompassed a temperature range from -40°F to 1000°F. Functional tests using 204 and 205 size bearings were run at speeds up to 30,000 rpm and temperatures to 1000°F. Under these operating conditions, a maximum life of 3-1/2 hours was obtained on a 204 size bearing equipped (OVER)

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with a Clevite 300 retainer. Attempts to employ light-weight, Teflon impregnated porous metal composites as self-lubricating retainers in high speed ball bearings were unsuccessful. No further testing of these particular materials is anticipated.

FOREWORD

This technical report was submitted in May 1978 by the Westinghouse Research and Development Center, 1310 Beulah Road, Pittsburgh, PA 15235, under Contract F33615-77-C-2027. It describes work performed during the period April 1, 1977 to April 28, 1978. The effort was sponsored by the Air Force Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson AFB, Ohio, under Project 3048 (Aerospace Fuels and Lubrication), Task 304806 (Aerospace Lubrication) and Work Unit 30480698 (Development of Light Weight Solid Lubricated Bearing Retainers). Mr. John B. Schrand/AFAPL/SFL administered the project for the Air Force. Mr. David J. Boes of the Westinghouse Research and Development Center was technically responsible for the work.

Acknowledgment is hereby given to Messrs. G. R. Kelecava, T. J. Cronin, and R. J. Szepesi for the preparation and conduct of the reported functional tests and for their otherwise very generous support to this program.

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- In Phase 3, four self-contained, solid lubricated ball bearings -- two from each of the previous phases of the program -- were to be operated at 60,000 rpm and the maximum temperature for which the self-lubricating retainer was developed.

SECTION II

BACKGROUND DISCUSSION

1. Material Considerations

In applications encompassing ultra-high speeds and moderate to high temperatures, such as the zero to 60,000 rpm and $600^{0}F$ to $1000^{0}F$ requirements of this program, it is imperative that the ball bearing retainer, employed as the lubricating component, possesses mechanical properties capable of tolerating the centrifugal forces imposed upon it. It is well known that metal matrix, self-lubricated composites are inherently weaker, structurally, than a truly sintered metallic composite formed through powder metallurgy techniques. This is due to the fact that in order to impart low friction-wear characteristics to the composites, it is necessary to incorporate into their matrix relatively large quantities of solid lubricants, such as polytetrafluoroethylene (PTFE) or molybdenum disulphide (MoS_2). This lack of high mechanical strength, therefore, is considered the major obstacle in the development of an ultra-high speed, moderate temperature, solid lubricated bearing system. In addition, a recently completed analysis of heat generation in high speed, solid lubricated ball bearings indicated strongly that much of the heat generation in such a bearing system is the result of the excessive weight of the bearing retainer. In view of these observations, it became apparent that in order to achieve reasonably long life in a solid lubricated ball bearing operating in the 30,000 to 60,000 rpm range, the use of a high strength-light weight, self-lubricating retainer was mandatory.

One such material having the potential to satisfy the above requirements was generated during the performance of Air Force Contract AF33615-72-C-1626. Basically, the composite is comprised of a matrix of sintered, stainless steel fibers that has been impregnated with one or more materials having suitable self-lubricating characteristics. In its original form, the fiber matrix is quite porous, its density ranging between 15 and 20% of theoretical. Thus, considerable volume

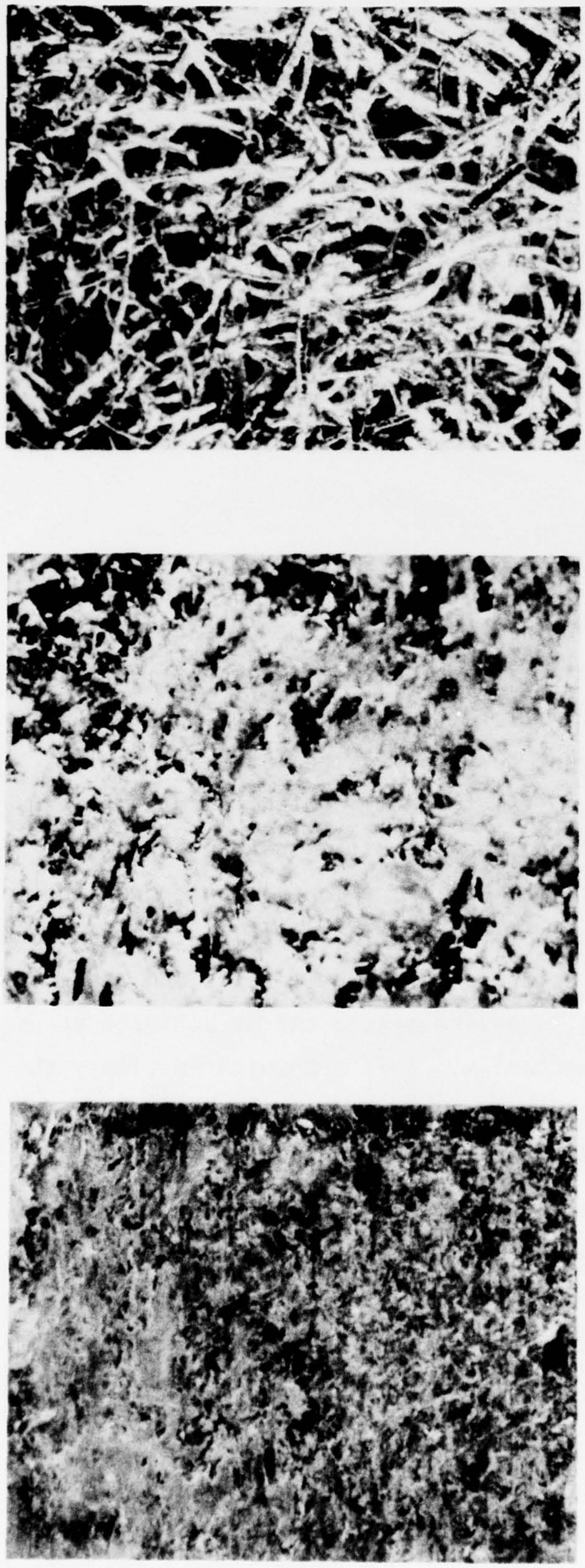
is available for lubricant impregnation. The types of lubricants suitable for use with this material include:

- waxy Teflon (m.p. $\sim 610^{\circ}F$),
- polyimide polymers dissolved in a suitable solvent and doped with various solid lubricants, such as a molybdenum disulphide and/or Teflon, and
- various fluoride eutectics having melting points above $1400^{\circ}F$.

In the case of waxy Teflon (WTFE) and fluoride eutectics, impregnation is achieved through submersion of the fiber matrix in the lubricant at a temperature above the lubricant's melting point. Polyimide polymers can be carried into the matrix by means of repeated impregnations and solvent-evaporation operations. Subsequent to its impregnation, the body is inserted into a suitable die and hot pressed under high pressure to provide additional mechanical strength and lubricant distribution. Figure 1 presents three macrophotographs of the material in (a) the green, or unfilled state; (b) the impregnated condition; and (c) the final, hot-pressed form. This particular composite consists of a stainless steel fiber matrix (15% theoretical density) containing waxy Teflon as the lubricant.

2. Waxy Teflon (WTFE) Preparation

Chemical modification of the Teflon (PTFE) employed in the self-lubricating composites studied in this program results in a significant reduction in both the friction coefficient and the wear rate of the composite. The physical properties of the PTFE are changed in such a way that it exhibits a sharp melting point at $\sim 610^{\circ}F$. As a result, its use in a self-lubricating load bearing composite at this temperature provides a thin, fluid film of the resin on the metal components with which it is in contact. In this way, dynamic friction coefficients and wear, of itself and of bearing components, are reduced. The resin is modified in the following manner.



Unfilled

Teflon Impregnated

Teflon Impregnated
and Hot Pressed

Figure 1—Macrophotographs of Teflon-filled, stainless steel matrix composite. 24X

Approximately 200 grams of powdered PTFE ($\sim$100 mesh) are weighed into a porcelain dish and placed in a furnace at 1100^{o}F for a period of 1-1/2 hours. Following this exposure, the material is removed and placed in a second furnace for 3 hours at a temperature of 700^{o}F. During this second firing, the modified PTFE changes in color from brownish-gray to pure white due to the removal of certain volatiles and carbonaceous components. When pulled from the furnace, the resin is in the molten state and quite viscous. Upon cooling, the solid material is then ground to a 40-50 mesh particle size.

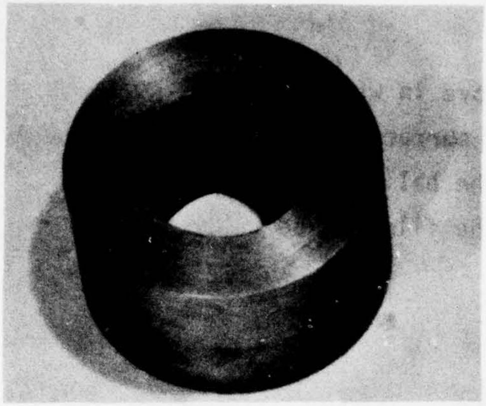
3. Lubricant Application Technique

The primary purpose of any lubricant in a load-bearing system is to prevent metal-to-metal contact and, thereby, prevent wear. In a solid lubricated load-bearing sytem, therefore, it is imperative that the lubricant not only thoroughly films the load-bearing surfaces, but also is available for replenishment purposes as the lubricant is lost due to wear. In a ball bearing, metal-to-metal contact occurs between the balls and the retainer (sliding) and the balls and the inner and outer races (primarily rolling). The balls are in sliding or rolling contact with every other component of the bearing system. If, therefore, a solid lubricating film can be established on these balls and replenished as needed, solid lubrication of the entire system can be achieved through what is called a film transfer mechanism. This mechanism is simply the transference of a solid lubricating film from one metal surface to another with which it is in sliding or rolling contact.

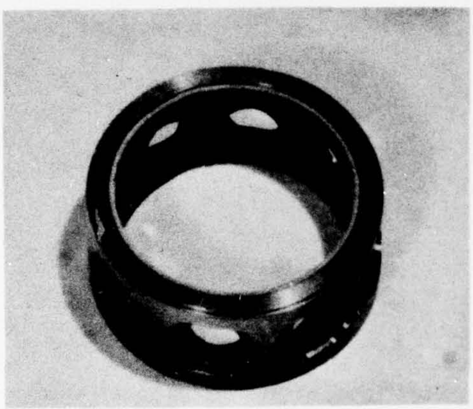
The technique employed in this program for accomplishing this type of lubrication in a ball bearing is to replace its metal retainer with a welded, double-shrouded retainer fabricated from a self-lubricating composite. Figure 2 is a series of photographs illustrating the various steps involved in the fabrication and assembly of one such bearing system.

In operation, minute quantities of lubricants are continuously metered to the balls in sliding contact with the retainer. The balls,

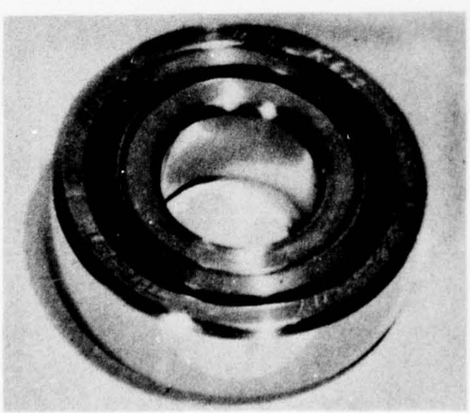
in turn, transfer this lubricant to the race groove in which they are rolling. In this way, all critical load bearing surfaces are coated with a thin, tenacious lubricating film. Since the balls are continuously sliding against the self-lubricating retainer, the film can be replenished if lost through wear.



Tungsten diselenide-gallium indium blank for 204 size bearing



Titanium, double-shrouded retainer machined from blank



204 size ball bearing equipped with shrouded retainer

Figure 2 — Application technique for WSe_2/GaIn double-shrouded composite retainers in ball bearings.

SECTION III

EXPERIMENTAL RESULTS

1. Test Facilities: 10,000 to 30,000 RPM

Five testing stations are available for functionally evaluating 204, 205, and 207 ball bearings at speeds from 10,000 to 30,000 rpm. One station is capable of simulating an altitude of ∿200,000 ft. Figure 3 is an overall view of the test laboratory with one vacuum shroud and one oven installed for illustration purposes. Spindle bearings and drive motors are water cooled. A hot worked, M-2 tool steel shaft, supported by 207 slave bearings, is direct-driven by a water cooled electric motor. The 2-pole motor is powered by a generator furnishing 510 cycles, 250 volt, 3-phase current.

Test bearings are directly loaded. It should be pointed out that a compensating bellows arrangement is used for the vacuum test stations where the loads are applied externally. The following data can be obtained from a test run: bearing temperature, oven temperature, environmental pressure, bearing speed, and bearing component wear. All shafts, housings, load devices and other components directly associated with test bearings operating up to 900°F are fabricated from M-2 tool steel hardened to R_C 58-60. All such components employed in 1200° and 1500°F functional tests are fabricated from Rene' 41.

In the majority of cases, all functional tests described in this report were permitted to operate to failure. The time of bearing failure was selected as the point at which the operating temperature of the bearing exceeded the test temperature by approximately 30°F. This temperature rise usually occurred quite abruptly and invariably indicated that contact had occurred between one or more of the balls and the reinforcing metal shrouds. This, in turn, indicated either excessive pocket wear or retainer fracture in the ball pocket bridge.

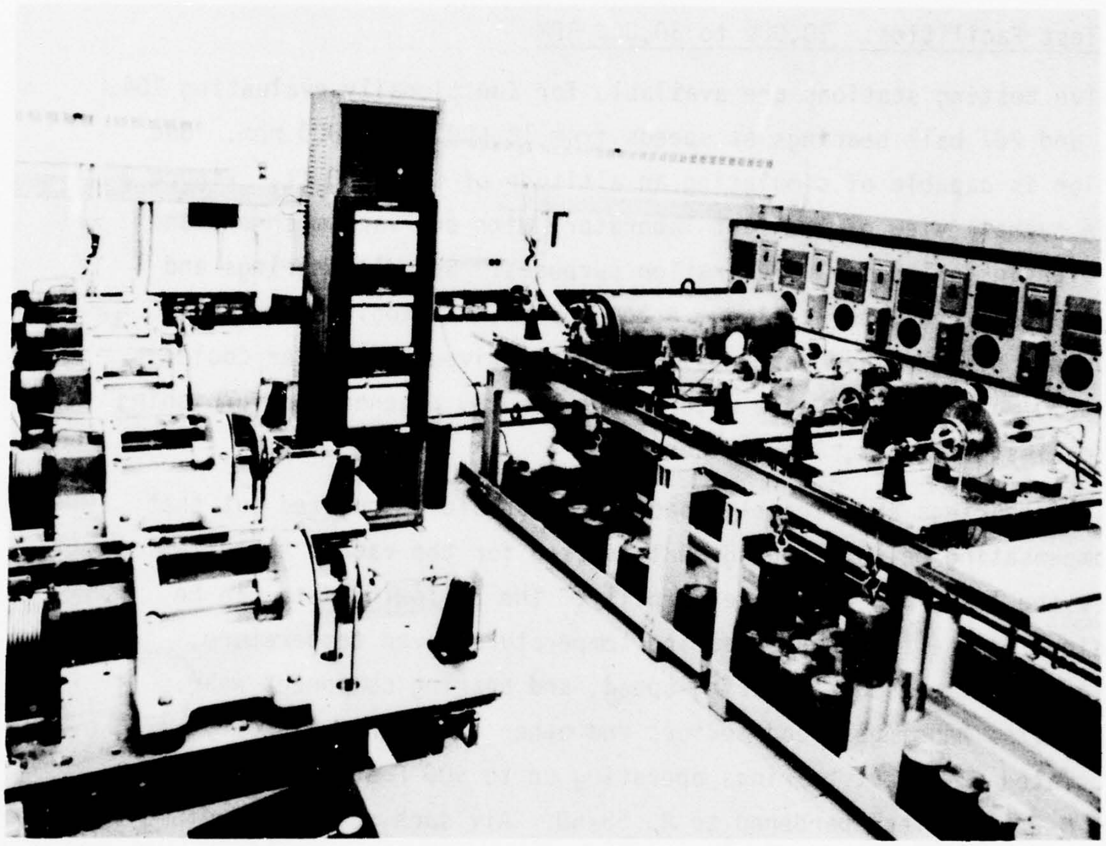


Figure 3 — **High speed bearing test laboratory.**

2. <u>High Speed Test Facility: Variable Speed to 60,000 RPM</u>

A facility capable of functionally evaluating the performance of self-contained, solid lubricated ball bearings over a 60,000 rpm speed range at temperatures up to $600^{o}F$ was also available to this program. Figure 4 is an overall view of the test rig. Basically, the device consists of a variable speed drive coupled to a transmission having a 15:1 gear ratio. The transmission in turn, is coupled through a double, shear spline to the ball bearing test cartridge. The propulsion unit is a Westinghouse 22-1000, 40 HP adjustable speed, DC motor. It is capable of operating at a maximum speed of 4150 rpm, regulated to within $\pm 1\%$ by means of a separate tachometer. The unit includes a solid state Thyrister controller and operator's station. Speed is infinitely variable over the full 60,000 rpm range.

The high speed transmission is a Model 215D, modified by the Cotta Transmission Company for operation at 60,000 rpm. The 15:1 ratio unit is equipped with a pressure lubrication system furnishing oil mist on bearings and spray jet on gears. A water to oil heat exchanger is an integral part of the unit, and is equipped with over-temperature and under-pressure safety cut-out devices.

Coupled to the high speed output shaft of the transmission is a bearing test fixture that was designed and fabricated in this laboratory. Figure 5 is a photograph of this unit mounted on the high speed transmission. As shown in the exploded view of Figure 6, the dual test bearings are preloaded by means of six springs contained in a cartridge that, in turn, is loaded against the inboard bearing's outer race. The springs provide a total load of 66 lbs in thrust which can be reduced to 33 lbs by the removal of every other spring. The test bearing shaft is coupled to the high speed output shaft of the transmission by means of a quill containing a central shear section and an internal spline on either end. This safety device is designed to shear when combined test bearing torque exceeds 8 ft lbs. In this way, catastrophic failure of the transmission's output shaft and integral, precision gearing is avoided. Use of the double spline in conjunction with relatively loose

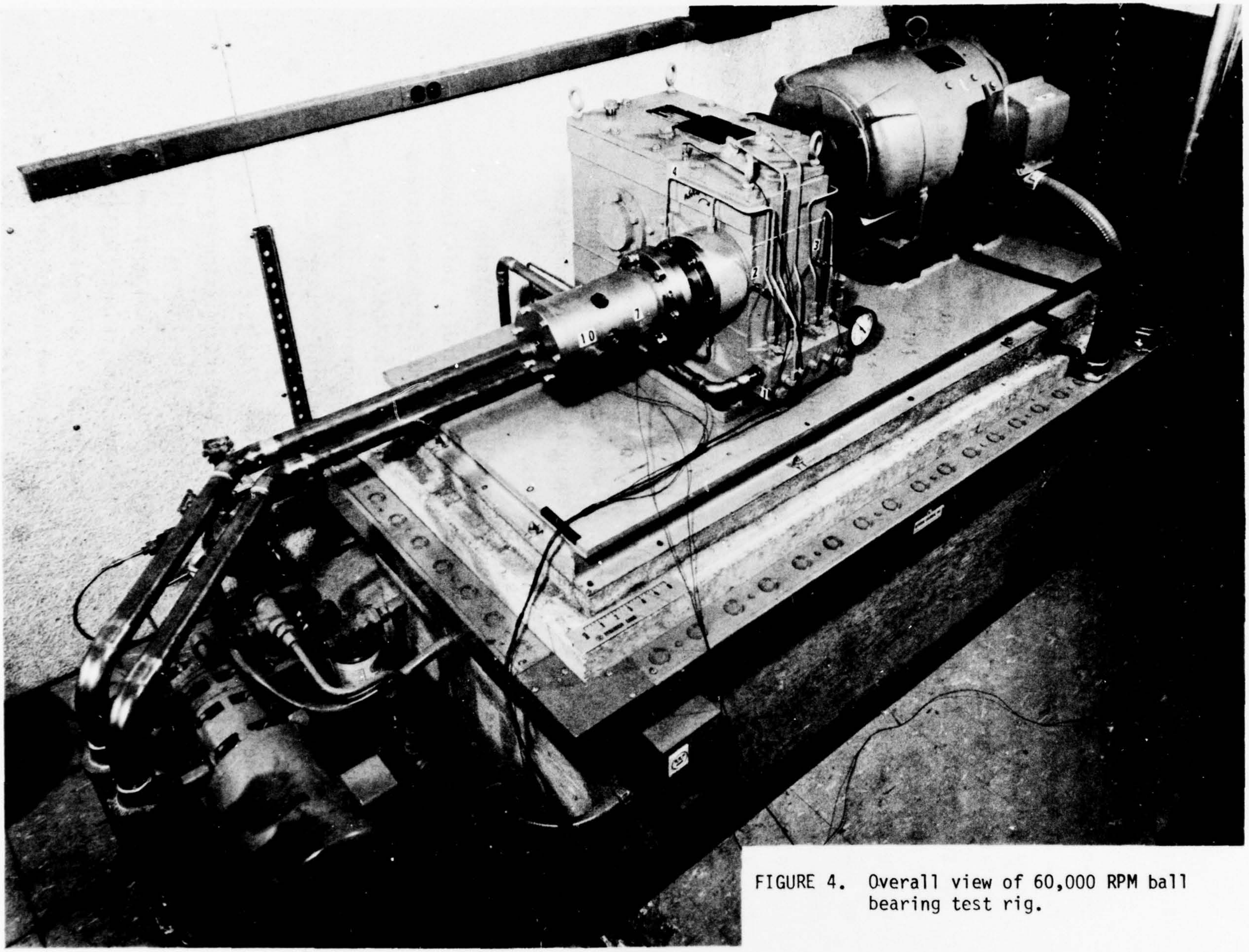


FIGURE 4. Overall view of 60,000 RPM ball bearing test rig.

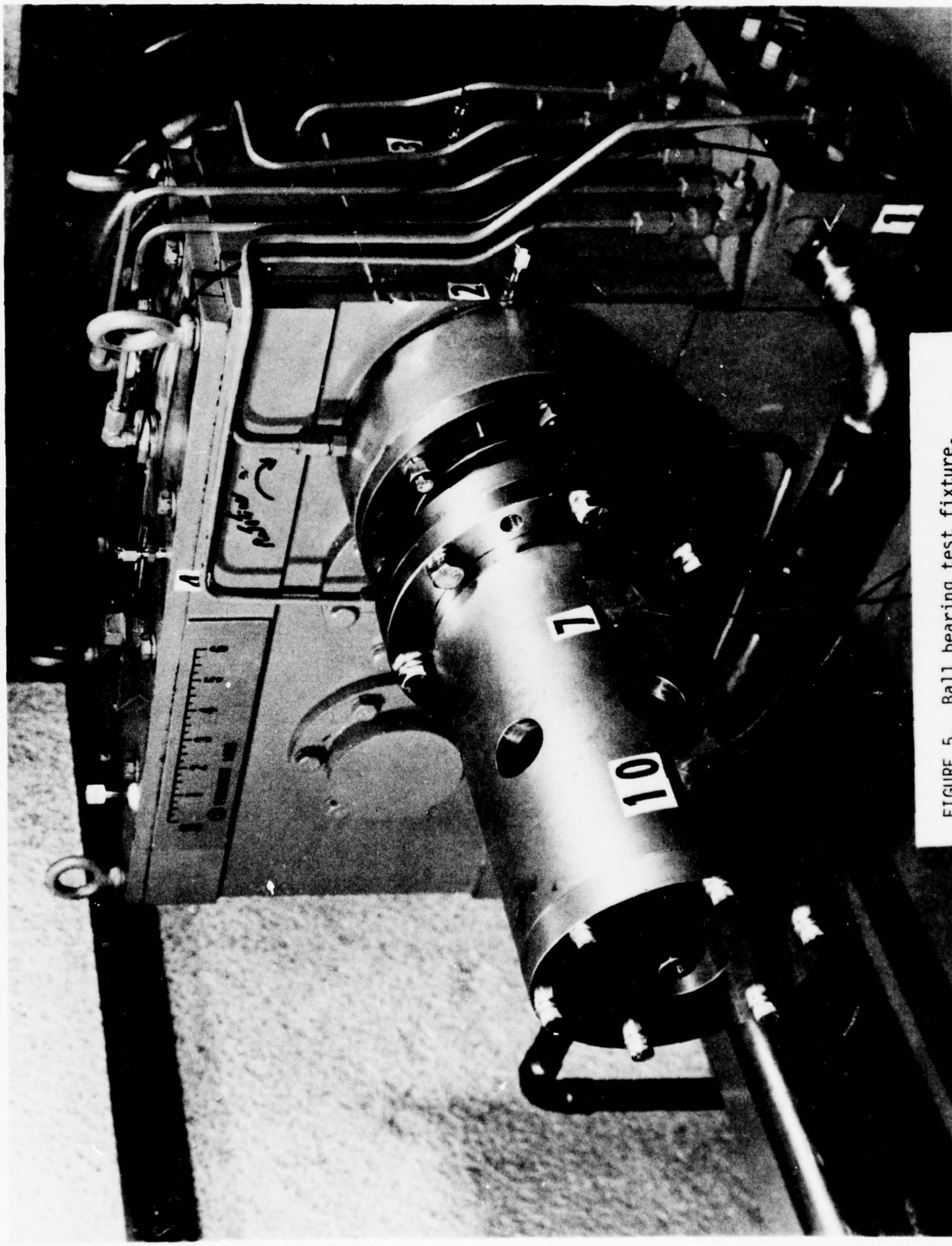


FIGURE 5. Ball bearing test fixture.

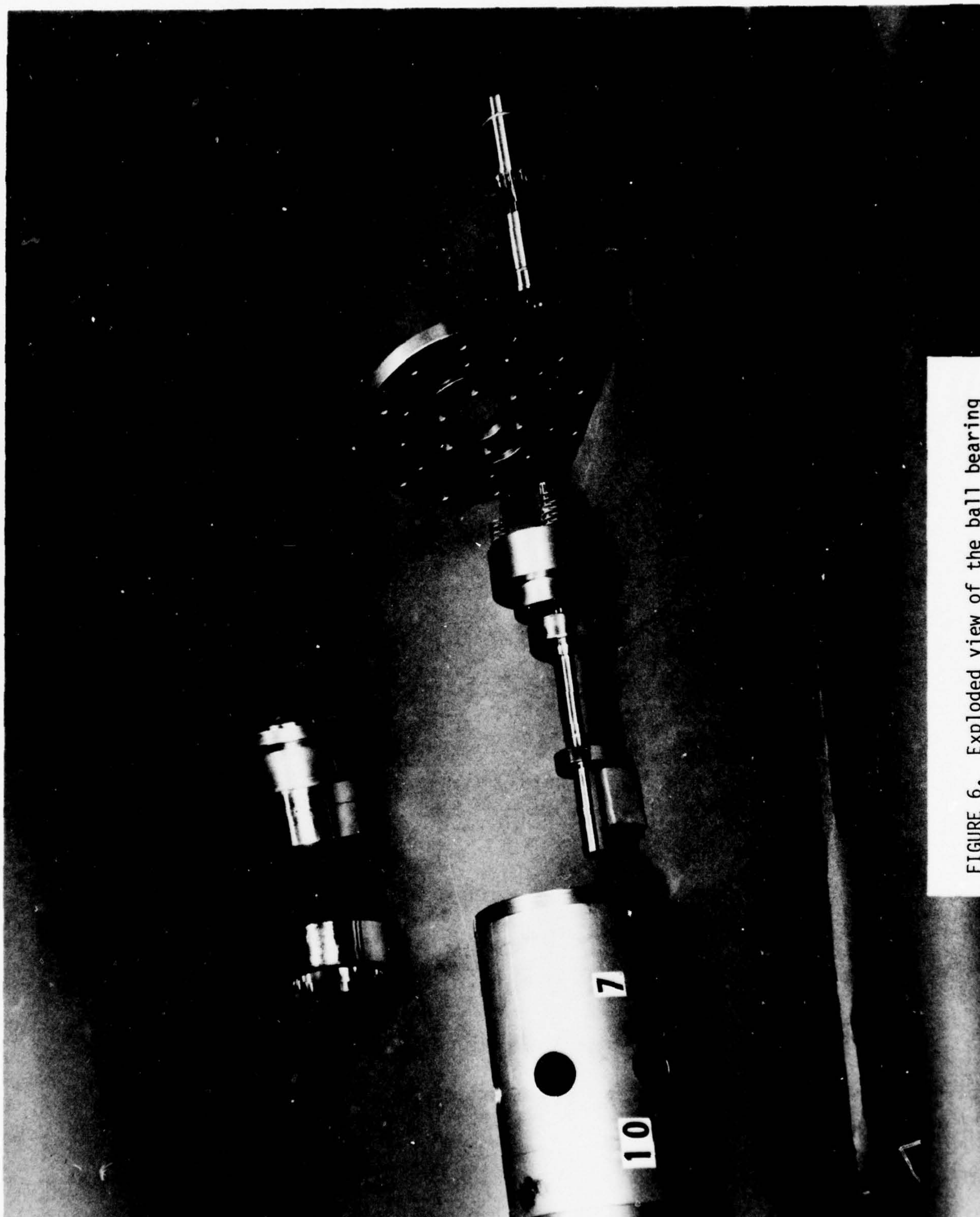


FIGURE 6. Exploded view of the ball bearing test cartridge.

fits between the mating splines provides a flexible coupling system for 60,000 rpm operation in which the concentricity of the two shafts and total run-out are no longer critical parameters.

3. Functional Bearing Test Results

3.1 Waxy Teflon Infiltrated Feltmetal* Retainers

A total of six functional tests was performed on 204 ball bearings equipped with retainers fabricated from 430 stainless steel Feltmetal infiltrated with waxy Teflon (WTFE). Table 1 presents the results of these tests. The quantity of Teflon contained in the composites varied from 40 to 70% (vol). The composite from which the retainer employed in Run 1 was machined was fabricated as follows.

A 3 in. long x 1-1/2 in. wide x 3/8 in. thick piece of stainless steel Feltmetal 430 (10% Theo. density) was rolled into a 1-1/2 in. dia. x 1-1/2 in. long ring and inserted into the 204 ring die. The material was then compressed under a 2-1/4 ton load to provide a ring having final dimensions of 1.5 in. O.D. x 0.81 in. I.D. x 0.56 in. thick and a density of 1.8 g/cc. The piece was then vacuum impregnated with WTFE at $700^{o}F$ and 70 lb/in^2 over a 2-1/2 h period. The final density of the piece was found to be 3.1 g/cc, and contained 63% (vol) WTFE. As noted in Table 1, an operating life of only 4 h was obtained on a bearing using this composite as a self-lubricating retainer before failure occurred due to ball pocket bridge cracking. This type of failure indicated a lack of mechanical strength in the composite.

In an attempt to achieve better penetration and a higher strength in the Feltmetal bodies, a new technique for filling this material was attempted. Rather than using relatively low, dead-weight loading or gas pressure to force the molten Teflon into the piece, it was decided to attempt to employ much higher pressures by means of a hydraulic press. Using a ring die, and a 10 ton press, a 4 in. long x 1-1/2 in. dia.

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*Trademark of Brunswick Corporation.

TABLE 1. FUNCTIONAL TEST RESULTS - 204 BALL BEARING

RETAINER MATERIAL: Waxy Teflon Infiltrated Feltmetal*

Run No.	Code No.	Speed RPM	Temp. °F	Load-lbs Thrust	Load-lbs Radial	WTFE Vol %	Life Hrs	Comments
1	6	10,000	600	50	50	63	4	Breakout of one ball pocket bridge.
2	10	10,000	600	50	50	50	35	Pocket bridge breakout at material seam.
3[(a)]	11	10,000	600	50	50	50	10	Pocket bridge breakout at material seam.
4	15	21,500	600	50	25	40	1½	Pocket bridge breakout at material seam.
5[(b)]	17	21,500	600	50	50	40	4	Pocket bridge breakout at material seam.
6[(b)]	25	21,500	600	50	25	70	2½	Heavy pocket wear.

*Brunswick Trade Name

(a) Material Seam Heliarc Welded

(b) 7 Ball Complement Rather than 8

Feltmetal piece, submerged in 60 g of molten WTFE, was subjected to a pressure of 15,000 psi at 700^{o}F for a 3-minute period. By employing very close fits between the rams and the die cavity, very little molten Teflon was extruded out of the die despite the high pressure involved. Subjecting the piece to this high pressure condition resulted in a reduction in length to 1-1/2 in. and a 50% (vol) fill of WTFE. Figure 7 is a photograph of the original Feltmetal, rolled ring and the WTFE infiltrated compressed blank. It was decided to employ this second technique to fabricate all experimental Feltmetal/WTFE composites.

Runs 2 and 3 were performed on 204 ball bearings equipped with Feltmetal retainers containing 50% (vol) waxy Teflon. The bearings operated for periods of 35 h and 10 h, respectively. In both cases, bearing failure was caused by ball pocket bridge "break-out" at that position where the seam of the Feltmetal ring was located. An attempt to reinforce the ring at this location through Heliark welding prior to infiltration was unsuccessful, as evidenced by the results of Run 3.

The remaining experiments (Runs 4-6) performed on 204 ball bearings equipped with Feltmetal/WTFE retainers were operated at a speed of 21,500 rpm and a temperature of 600^{o}F. As noted in Table 1, operating lives of very short duration were realized despite reductions in load and ball complement. In all cases, failure was caused by high retainer wear and excessive heat generation due to the high friction characteristics of the stainless steel matrix. For these reasons, experimental work on this material was discontinued.

3.2 Carbon-Graphite Matrix Containers

3.2.1 Physical Properties and Friction Characteristics

In an effort to achieve a reduction in the dynamic friction coefficient of candidate retainer materials while also satisfying the low weight requirements of this program, attention was directed at carbon-graphite materials that are available in a wide range of porosities. Table 2 presents pertinent physical properties of the various grades evaluated

TABLE 2

PHYSICAL PROPERTIES[a] OF VARIOUS GRADES OF CARBON-GRAPHITE

Grade	Bulk Density g/cc	Porosity Vol %	Strength lb/in² Compression	Flexural	Tensile
Porous Carbon					
Grade 25	1.03	48	800	300	100
Grade 45	1.04	48	900	500	200
Grade 60	1.05	48	1,000	600	300
Porous Graphite					
Grade 25	1.03	48	400	200	70
Grade 45	1.04	48	500	300	150
Grade 60	1.05	48	600	400	200
Grade AGSR	1.58	30	5,200	2,600	-
Grade CS	1.72	24	5,000	2,400	-
Grade ATJ	1.73	10	8,300	4,000	3,500
Grade CNFJ	1.82	1	30,000	9,300	8,000
Grade CDJ	1.75	7	36,300	8,500	7,000
Grade CDJ-83	9.76	5	36,300	8.800	7,000
Grade 2413[b]	1.55	20	7,000	2,500	1,000
Grade H-002[c]	1.59	29	17,200	9,000	5,500
Grade P5-Ag[d]	2.35	5	45,000	13,000	10,000

NOTE:

Data Furnished By:

(a) Union Carbide Corporation
(b) The Wickes Corporation
(c) Great Lakes Carbon Corporation
(d) Pure Carbon Company

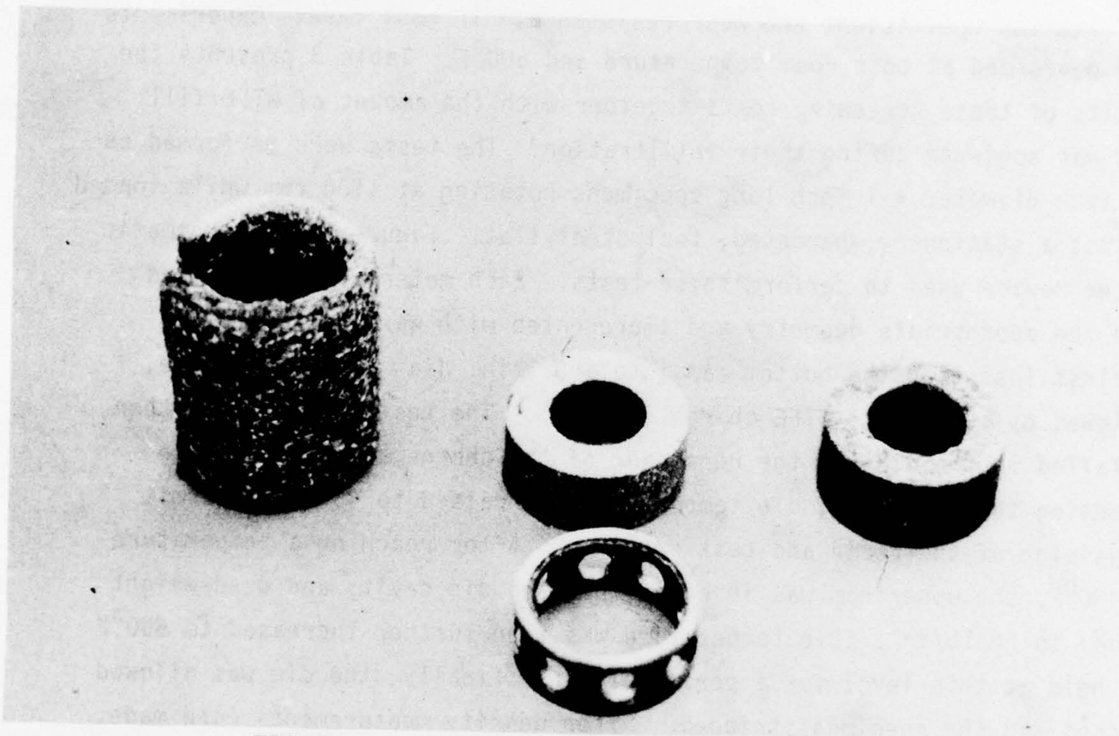

FIGURE 7. Steps in making feltmetal blank.

during this program. It will be noted that the porosity of these materials ranges from a low of 1% (vol) to a high of 48% (vol). Those materials possessing a porosity of 10% (vol) or more were selected for infiltration with waxy Teflon, while those of lower porosities were evaluated directly as retainers in test bearings. Prior to their application in functional ball bearing tests, however, each material was evaluated with respect to its friction coefficient and wear resistance. In most cases, experiments were performed at both room temperature and 600^{o}F. Table 3 presents the results of these screening tests together with the amount of WTFE fill that was achieved during their infiltration. The tests were performed on 0.5 inch diameter x 1 inch long specimens rotating at 1100 rpm while loaded against a stationary, hardened, tool steel flat. Figure 8 is a schematic of the device used to perform these tests. Each material was machined into the appropriate geometry and impregnated with waxy Teflon (WTFE) by first inserting the bottom ram into a 0.5 in. dia tool steel die, followed by 50% of the WTFE charge ($\sim$3,5 g). The test specimen was then installed in the die and the remainder of the charge added. Prior to inserting the upper ram, die temperature was raised to 450^{o}F to permit outgassing of the resin and test specimen. After reaching a temperature of 450^{o}F, the upper ram was inserted into the die cavity and dead-weight loaded to 50 lb/in^2. Die temperature was then further increased to 650^{o}F and held at this level for a period of 2 h. Finally, the die was allowed to cool and the specimen stripped. After density measurements were made, the friction coefficient and wear characteristics of each material were evaluated.

3.2.2 Ball Bearing Tests

A total of twenty functional tests were performed on 204 and 205 size ball bearings equipped with carbon-graphite matrix retainers. In all but one case, titanium shrouds were employed as reinforcing members for the retainer. In the majority of tests, a combined load of 50 lb thrust/ 25 lbs radial was employed at speeds ranging from 10,600 rpm to 30,000 rpm and temperatures up to 820^{o}F. Table 4 summarizes the results of these experiments.

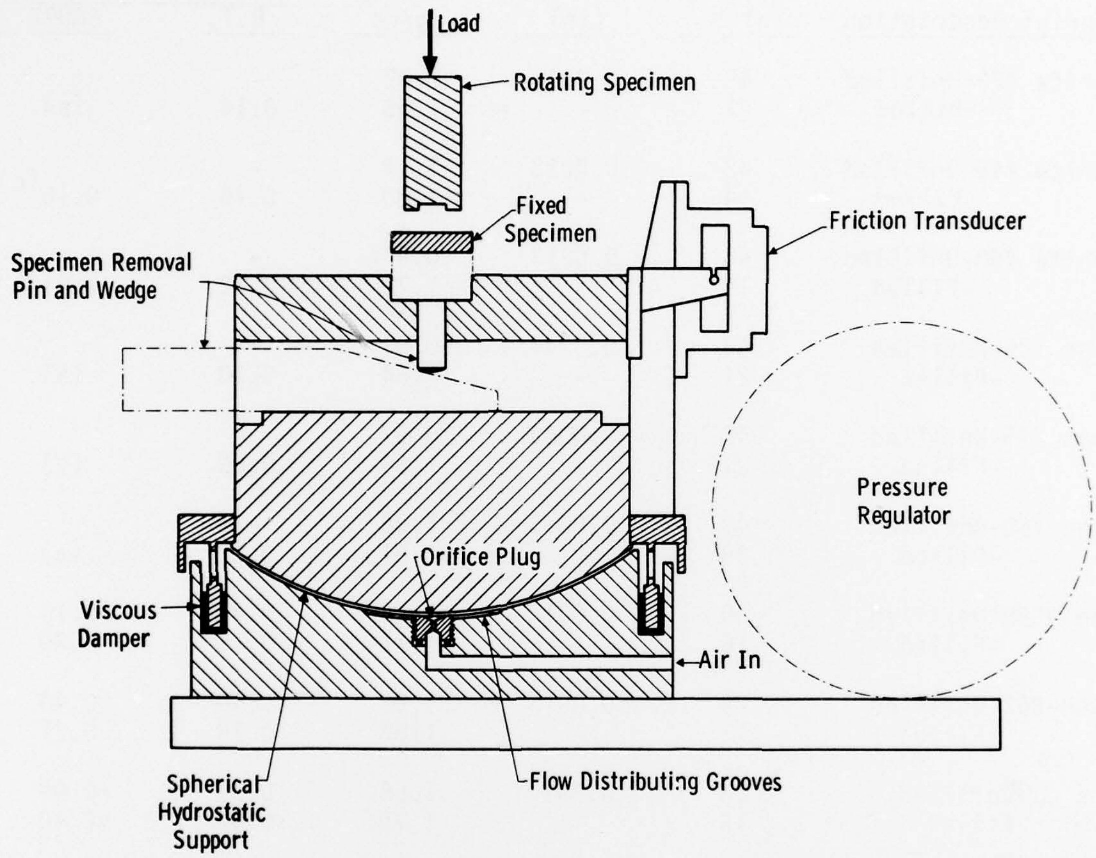

FIGURE 8. Schematic of friction-wear tester.

TABLE 3

PHYSICAL PROPERTIES OF VARIOUS TEFLON-FILLED CARBON-GRAPHITE COMPOSITES

Material Description	Porosity Vol %	Pore Dia. (in)	Density g/cc	Friction Coefficient 600 lb/in^2-15 FPM R.T.	600°F
Graphite #25-Unfilled	48	0.0047	1.02	-	
-Filled	21	-	1.66	0.14	(a)
Graphite #45-Unfilled	48	0.0023	1.14	-	
-Filled	14	-	1.80	0.15	0.18(c)
Graphite #60-Unfilled	48	0.0013	0.97	-	
-Filled	15	-	1.79	0.12	0.21(c)
Carbon #25-Unfilled	48	0.0047	0.93	-	
-Filled	21	-	1.64	0.13	(a)
Carbon #45-Unfilled	48	0.0023	0.97	-	
-Filled	21	-	1.66	0.09	(a)
Carbon #60-Unfilled	48	0.0013	1.06	-	
-Filled	29	-	1.81	0.12	(a)
Grade AGSR-Unfilled	30	∼0.001	1.48	0.21	0.40
-Filled	16	-	1.77	0.15	0.20
GradeH-002-Unfilled	29	∼0.001	1.63	>0.40	>0.40
-Filled	11	-	1.88	0.19	0.21
Grade CS-Unfilled	24	<0.001	1.68	0.30	>0.40
-Filled	15	-	1.79	>0.40	>0.40
Grade ATJ-Unfilled	23	<0.001	1.73	-	-
Filled	12	-	1.86	0.29	0.29
Grade 2413-Unfilled	33	<0.001	1.41	>0.40	>0.40
-Filled	33		1.42	>0.40	>0.40
Grade CDJ(b)	7	-	1.75	0.48(c)	0.40
Grade CDJ-83(b)	5	-	1.76	0.08(c)	0.032
Grade CNFJ(b)	1	-	1.82	0.21(c)	0.10
Grade P5-Ag(b)	5	-	2.35	0.26	0.13

(a) Excessive Wear Rate

(b) Did Not Contain Waxy Teflon

(c) Reduced Load of 360 lb/in^2

TABLE 4

FUNCTIONAL TEST RESULTS

Retainer Material: Carbon-Graphite Matrices
Load: 50 lb Thrust/25 lb Radial

Run No.	Code No.	Speed RPM	Temp. °F	Retainer Material	PTFE Vol %	Bearing Size	Life h	Comments
7	2	10,600	600	Graphite 45	34	204	26	Ball/shroud contact due to wear.
8	3	10,600	600	Carbon 45	27	204	8	" " "
9	5	10,600	600	Graphite 60	33	204	45	" " "
10	4	10,600	600	Carbon 60	35	204	25	" " "
11	7	10,600	600	AGSR	13	204	14	" " "
12	9	10,600	600	AGSR + T-30	15	204	25	" " "
13*	13	10,600	600	AGSR + T-30	14	204	29	" " "
14	8	10,600	600	2413	3	204	10	Pocket bridge chipping and breakout.
15	19	10,600	600	CNFJ	-	204	0.5	Heavy chipping-ball pockets
16	20	10,600	600	CNFJ + T-30	<1	204	2	Heavy chipping-ball pockets
17	18	10,600	600	CDJ + T-30	<1	204	1.5	Severe cracking-chipping
18	22	21,500	500	CDJ + T-30	<1	204	0.25	Excessive roughness-chipping
19**	21	21,500	800	P5-Ag	-	204	0.50	Shroud slipped on retainer
20*	24	21,500	700	P5-Ag	-	205	0.10	No shrouds used-catastrophic failure
21	26	21,500	700	P5-Ag	-	205	0.50	Shrouds pinned - retainer cracking
22	23	21,500	600	ATJ	-	205	0.25	Shroud slipped on retainer
23A	27	30,000	700	ATJ	-	205	0.25	Test stopped for inspection
23B	27	30,000	820	ATJ	-	205	1.25	Retainer cracking at pocket bridge
24	28	30,000	700	H-200	16	205	1.25	Retainer cracking
25	33	30,000	625	CDJ-83	-	204	0.25	Retainer chipping-cracking

*Load: 50 lb thrust/50 lb radial

**Load: 25 lb thrust/50 lb radial

Runs 7 and 8 were performed on 204 bearings equipped with WTFE filled graphite 45 and Carbon 45 retainers, respectively. The retainers were infiltrated with WTFE in a tool steel ring die at 700^{o}F and a dead weight load of 50 lb/in^2. The bearings operated smoothly at 10,600 rpm and 600^{o}F for periods of 26 h and 8 h, respectively, before contact occurred between a number of the bearing balls and the retainer shroud. This contact resulted in a sharp increase in bearing temperature and rapid bearing failure.

Runs 9 and 10 were performed under identical operating conditions as the two previous experiments, but incorporated the slightly stronger Graphite 60 and Carbon 60 materials. In addition, the retainer blanks were infiltrated with WTFE at 70 lb/in^2 helium pressure after a vacuum furnace in which they were held had reached 700°F. It will be noted that the use of slightly stronger materials and vacuum infiltration did result in a modest increase in life to 45 h and 25 h, respectively. In the writer's opinion, however, bearing life, as well as retainer strength and wear resistance, remained inadequate to satisfy the ultra-high speed requirements of this program. For these reasons, further work on highly porous carbon and graphite bodies as bearing retainers was terminated, and emphasis placed on the mechanically stronger carbon-graphite pieces possessing lower porosities and significantly smaller pore sizes. It was anticipated that the carbon-graphite matrix would contribute to the solid lubrication of the bearing system and that a reduction in WTFE content, combined with the increased mechanical strength of the composite, would result in reduced retainer wear, less chipping, and longer bearing life. As will be noted from the remaining test results summarized in Table 4, however, this was not the case. The remaining functional tests performed at 10,600 rpm and 600^{o}F (Runs 11 through 17) demonstrated that as WTFE content was reduced in the carbon-graphite matrix due to lower porosities, bearing operating life also dropped sharply. In all cases where Teflon content was <5% (vol), bearing failure was caused by severe retainer chipping, particularly in the ball pocket areas.

The remaining experiments listed in Table 4 were performed at speeds of 21,500 rpm and 30,000 rpm using a variety of high strength, carbon-graphite materials as the bearing retainer. Operating temperatures ranged from 600°F to 820°F. In no case was an operating life in excess of 1 h - 25 minutes achieved. Shroud slippage and retainer cracking were the primary causes of bearing failure.

3.3 Miscellaneous Retainer Materials

Table 5 summarizes the test results of experiments made on 204 ball bearings equipped with self-lubricating retainers fabricated from a number of commercially available composites. The majority of the experiments were performed at a speed of 30,000 rpm and temperatures ranging from 400°F to 1000°F. The maximum life reached during this series of experiments was obtained on a bearing system equipped with a Clevite 300* retainer. Clevite 300 is an alloy comprised of 70% Fe, 15% Co, 15% Mo (wt %) whose density is approximately 97% of theoretical. The material is a powdered metal product having a hardness of RC 35-37. The alloy is self-lubricating at temperatures between 600°F and 1500°F by virtue of the complex, stable, and adherent oxide film formed upon exposure to high temperature -- oxidizing conditions. As will be noted in Table 5, the bearing equipped with a retainer fabricated from this material operated for a period of 3-1/2 h before material flow in the pocket bridges resulted in physical contact between the retainer and the inner race ball groove. This caused an increase in running torque and test shutdown. No retainer fracture or chipping was observed upon post-test examination. Heavy ball wear, however, was observed. It should be pointed out that while the ambient temperature of the test was held at 800°F, bearing temperature -- due to frictional heating -- was 1000°F. It is postulated that since the balls are in sliding -- rather than rolling -- contact with the pocket bridges, localized temperatures in these areas were considerably greater than 1000°F, causing a reduction in material strength and resultant material flow. Obviously, additional lubrication, provided by a solid lubricant possessing adequate oxidation resistance, is required in these areas. One such lubricant is the fluoride eutectic. Infiltration

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*Trademark of Gould Corporation.

TABLE 5

FUNCTIONAL TEST RESULTS - MISCELLANEOUS RETAINER MATERIALS

Run No.	Code No.	Speed RPM	Temp. °F	Retainer Material	Bearing Size	Load-lb Thrust	Load-lb Radial	Life h	Comments
26	1	10,600	600	Garfil[(a)]	204	50	50	5	Ball/shroud contact.
27	16	21,500	RT	Garfil	204	50	50	1.5	Ball/shroud contact.
28	29	30,000	400	Duroid 4300[(b)]	204	25	50	1	Material flow in ball pockets.
29	30	30,000	400	Duroid 5813	204	25	50	0.5	Material flow in ball pockets
30	31	30,000	1000*	Clevite 300[(c)]	204	50	25	3.5	Material flow in ball pockets. Heavy ball wear.
31	32	30,000	800	Clevite 300	204	50	25	4.5	Material flow in ball pockets. Heavy ball wear.
32	33	30,000	600	**	204	50	25	0.25	Retainer cracking and chipping.

(a) Garlock Bearings, Inc. - glass filament wound PTFE filled material.

(b) Dixon Corporation - filled Teflon matrix materials.

(c) Gould Corporation.

* Ambient temperature 800°F.

** Graphite 60 infiltrated with Thermid 600, a polyimide resin.

of a porous Clevite 300 body with one of the fluoride eutectics could conceivably provide a self-lubricating composite suitable for extreme temperature operation. This approach, however, has not been pursued.

In view of the short lives obtained on all candidate, self-lubricated ball bearing systems operating at speeds of 21,500 rpm to 30,000 rpm in the temperature range of $600^{o}F$ to $1000^{o}F$, this development effort was terminated.

SECTION IV

CONCLUSIONS

The effort devoted to this program did not achieve the primary goal of developing a self-contained, solid lubricated ball bearing system for reliable operation at 60,000 rpm and temperatures up to $1000^{o}F$. Neither Teflon infiltrated, porous metal matrices nor mechanically strong carbon-graphite bodies -- regardless of Teflon content - functioned satisfactorily as self-lubricating retainers under the required operating conditions. While the need for materials having low frictional characteristics could be met, it was found that their mechanical strength was inadequate and their wear rates excessive. On the other hand, those materials possessing high mechanical strength exhibited high friction coefficients and suffered excessive chipping and cracking during bearing operation. In the writer's opinion, a major breakthrough in the state-of-the-art of solid lubrication and self-lubricating composites will be required if the goals of this program are to be realized. What is needed are new solid lubricants of significantly improved oxidation resistance that retain their low friction characteristics over the entire -40° to $+1000^{o}F$ temperature range, as well as in a no-moisture or vacuum environment. In addition, mechanically strong composite matrices of equivalent oxidation resistance are needed that will hopefully contribute -- but at the least not be deleterious to -- the low friction characteristics of the solid lubricants that they contain.

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